Journal of Hydrology: Regional Studies 18 (2018) 156–167

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh

Assessing the potential impacts of dam operation on daily flow at ungauged river reaches

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ARTICLE INFO

Keywords:
Dam operation
Daily flow distribution
Unimodality
Degree of regulation index
Southern Quebec

ABSTRACT

Study Region: The study region is the Southern Quebec river network. Dataset on dams as well as daily flow recorded at stations were used.
Study Focus: Dam construction and operation can have significant impacts on hydrological regimes. If dam construction induces some basic alterations to basin hydrology, dam operation can introduce dynamic alterations in streamflow. Assessing the impacts of dam operation can be crucial for many applications where recorded flow series are used as a proxy for flow at nearby ungauged basins in regional flood frequency analysis or for hydrological modelling. The potential influence of dam operation on recorded flows was assessed through statistical testing that verified the unimodality of the daily flow distribution. The Degree of Regulation (DOR) index was then used to relate the potential influences of dam operation to basic physiographic and dam characteristics.
New Hydrological Insights for the Region: Application of a unimodality test to daily flow series recorded at stations located in the study region confirms that dam operation can result in non-unimodal daily flow distribution. Estimation of DOR values for all reaches of the study region shows that regulated river reaches could be potentially influenced by dam operation when DOR > 8. Of the 29% regulated river reaches (i.e. with one or more upstream dams), approximately 30% could be potentially influenced (DOR > 8) by dam operation.

1. Introduction

The construction of dams have altered the natural flow regimes of many watersheds across the world (Graf, 1999; Nilsson et al., 2005; Grill et al., 2015) and this will become even more important as dam construction is expected to continue increasing in the future (Zarfl et al., 2015). Dams have major impacts on hydrology as they can alter low flow regime and reduce peak flows, change the interannual flow variability (FitzHugh and Vogel, 2011; Magilligan and Nislow, 2005), and alter geomorphology and aquatic ecosystems (for a description of these impacts see Poff and Hart, 2002; Poff and Schmidt, 2016).

In order to evaluate the impact of dam construction on hydrological regimes, many studies have compared hydrographic characteristics estimated from pre- and post-dam construction on flows at downstream gaging stations (e.g. Magilligan and Nislow, 2005; Graf, 2006; Poff et al., 2006; Gao et al., 2009). Hydrological indices, inspired from those initially proposed by Richter et al. (1996) and The Nature Conservancy (2006), also called Indicators of Hydrologic Alteration (IHA), are often used to assess the hydrological changes resulting from dam construction. These studies showed that globally dams tend to decrease flow peak frequency, magnitude

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https://doi.org/10.1016/j.ejrh.2018.06.006
Received 4 October 2017; Received in revised form 28 May 2018; Accepted 22 June 2018
Available online 17 July 2018

and duration, while generally increasing the frequency, magnitude and duration of low flows (Magilligan and Nislow, 2005; Magilligan et al., 2003). Other impacts such as those related to downstream channel changes as a result of dams have also been analyzed (Schmidt and Wilcock, 2008).

Assessments of dam construction on streamflow by means of comparing pre- and post- dam hydrographic characteristics (e.g. annual peak flow or annual minimum flows) imply that some range of values are defined for natural flow regimes and that certain metrics are used to assess if post-dam values significantly differ from natural values (or pre-dam conditions). This type of comparison can be very challenging since many watershed characteristics (e.g. areas, altitudes, and latitudes) may influence hydrographic characteristics (e.g. low flow values, annual peak flow; Carlisle et al., 2010) and therefore the influence of dam construction cannot be unambiguously assessed in certain cases.

Assessing the specific impacts of dam operation are necessary if recorded flow series are used as a proxy for flow at nearby ungauged basins in regional flood frequency analysis or for hydrological modelling. In this sense, evaluating the specific impacts of dam operation can be important as non-operated dams can be assimilated to storage capacities. As pointed out by Villarini and Smith (2010), 'structural' alterations to basin hydrology, such as those induced by dams, are the norm for flood records, and analyses of flow distributions should reflect such anthropogenic changes. Dam operation however, can induced dynamic alterations to streamflow that may overlap with the more basic changes introduced by dam construction. Comparing pre- and post-dam construction flows does not allow for the separation of the impacts of dam construction from its operation.

Many studies have analyzed the influence of dam construction on flow regimes (e.g. Magilligan and Nislow, 2005; Assani et al., 2006; Lajoie et al., 2007; Gross and Moglen, 2007; Matteau et al., 2009; Peñas et al., 2016; Mei et al., 2017), but very few studies have looked at the specific impacts of dam operation on flows, i.e. how operations change flows in comparison to the situation where dams are not operated. White et al. (2005), using wavelet analysis, evaluated the impact of Glen Canyon dam (Colorado River) by comparing pre- and post-dam construction hourly flows at a downstream station. They showed that clear operating cycles related to hydroelectricity production could be detected from hourly flow series. Zimmerman et al. (2010) compared hourly flow series downstream of dams (flood control, run-of-river hydropower, and peaking hydropower) operated by the US Army Corps of Engineers on the Connecticut River basin to assess the potential impacts of dam operations on sub-daily flow regimes. These studies demonstrated that there was a distinctive signature for dam operation on sub-daily flow. Other more recent studies have also addressed this issue of dam operation on streamflows (e.g., Meile et al., 2011; Carolli et al., 2015; Chen et al., 2015; Bevelhimer et al., 2015). Collectively, these studies considered sub-daily flow series and only hydroelectric dams. The question however, remains if dam operation, other than hydroelectric dams, can also have an impact on daily flows and if other types of dams (e.g. flood control dams) may also have a 'detectable' impact on daily flow or a more general feature of the daily hydrogram.

The detection of characteristic signatures of dam operation on daily streamflow is difficult for many reasons. Firstly, operation records or operation rules are unknown and, in many cases, operation status (i.e. is the dam operated or not?) is even unknown. Secondly, even when operation records are available, operations have an impact on the short term flow and it remains difficult to assess their overall impact on hydrographs. Furthermore, operation frequency can vary considerably from one dam to another depending on the specific use of the dam (e.g. hydroelectricity production, flood control), thus making it even more difficult to detect the possible impacts on downstream flow. Incidentally, studies have reported the impacts of dam operation on sub-daily flow records arguing that flow variability changes induced by dam operation mainly affects sub-daily flow and that a daily time scale is to coarse to characterize the possible influence of dam operations (White et al., 2005; Zimmerman et al., 2010). Additionally, it remains difficult to specifically assess the impacts of operations on downstream recorded flow, given that stations are located at varying distances from operated dams. Finally, upstream watersheds may include many dams being operated to varying degrees with varying operation schedules, therefore increasing the difficulty of identifying distinct signatures of dam operation on recorded flows.

The main goal of this study was to define an index that can be readily estimated at any ungauged river reach from the available watershed and dam characteristics, thus providing information about the potential impacts of dam operations on streamflow. This was achieved through three main sub-objectives. First, we investigated the impact of dam operation on recorded daily flow. Herein, we propose a novel hydrological indicator of dam influence based on the unimodal or multi-modal character of the daily flow distribution. This indicator was validated through a comprehensive analysis of all streamflow records available for southern Quebec. Second, we propose an index based on readily available dam and hydrographic characteristics to assess the potential influence of dam operation on ungauged river reaches. Finally, we have applied the proposed index to a river network in southern Quebec and generated a map assessing the potential influence of dam operation on each reach.

The present study is organized as follows. Section 2 describes the dam and station datasets used in this study. Section 3 describes how the various dam configurations upstream of each station were structured in order to analyze the potential influence of dam operations on recorded flow. Section 4 describes the unimodality test and presents the results for the unregulated and regulated watersheds upstream of daily flow gauging stations. Section 5 presents the index, based on readily available dam and watershed characteristics, used to assess the potential influence of dam operation at ungauged river reaches. Section 6 presents some results of the global application of this index to the hydrographic network of Southern Quebec. Finally, conclusions and perspectives for future work are presented in Section 7.

2. Datasets

2.1. Dam dataset

Dataset from the *Répertoire des barrages du Québec* (*Quebec Dam Register* available at http://www.cehq.gouv.qc.ca/barrages/) was